JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Modeling the Response of the Lunar Exosphere to the Release of Spacecraft Exhaust Volatiles

Parvathy Prem, Dana M. Hurley
Johns Hopkins University Applied Physics Laboratory
SSERVI DREAM2 and LEADER Teams

July 25th, 2019
6th NASA Exploration Science Forum

SERVI — Solar System Exploration Research Virtual Institute
XSEDE — Extreme Science and Engineering Discovery Environment
TACC — Texas Advanced Computing Center

Background: 'Descending Toward the Moon', Chesley Bonestell, 1951

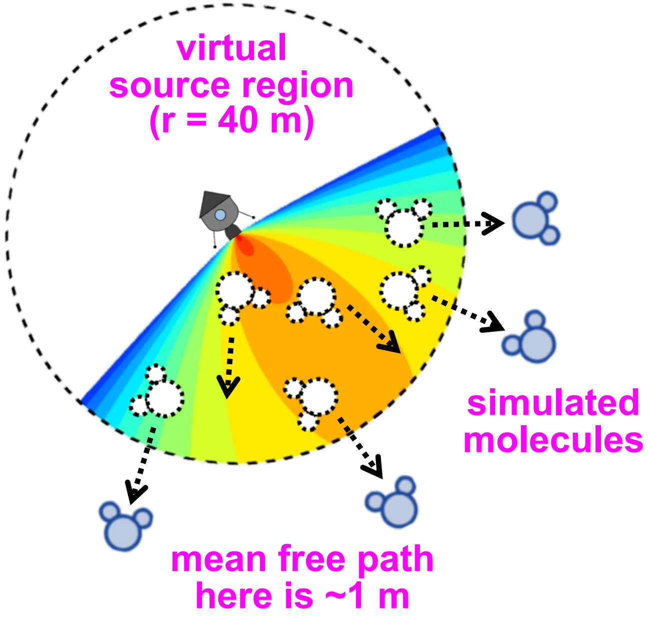
The Once and Future Exosphere

- **Almost any landed lunar mission will be an active volatile release experiment.**
  - Well-recognized during the Apollo era (e.g., **Milford & Pomilla, 1967**, **Aronowitz et al., 1968, Chang, 1969**), and worth revisiting (e.g., **Hurley et al., 2014, Shipley et al., 2014**).
  - Models are critical to interpreting observations from orbit and the surface.

- Why does this matter?
  - **Solar system science:** How do volatiles interact with the surfaces of airless bodies? Key to interpreting the lunar polar volatile record, understanding the behavior of surface boundary exospheres.
  - **Mission planning:** How do spacecraft alter the lunar environment? How should we account for this when planning surface operations and measurements?
  - **Resource characterization:** On what timescales is polar water renewed?

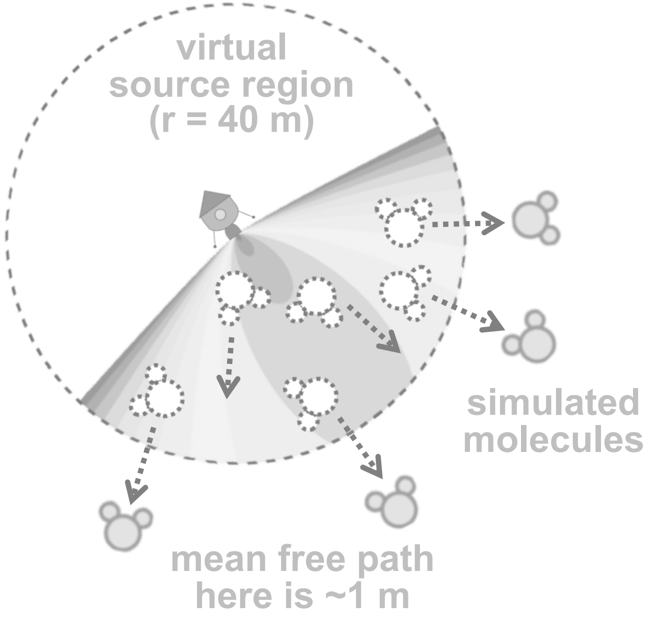
- Motivating questions:
  - How does the lunar exosphere respond to a powered landing?
  - How sensitive are observables to gas-surface interaction parameters?

To Make An Exosphere From Scratch

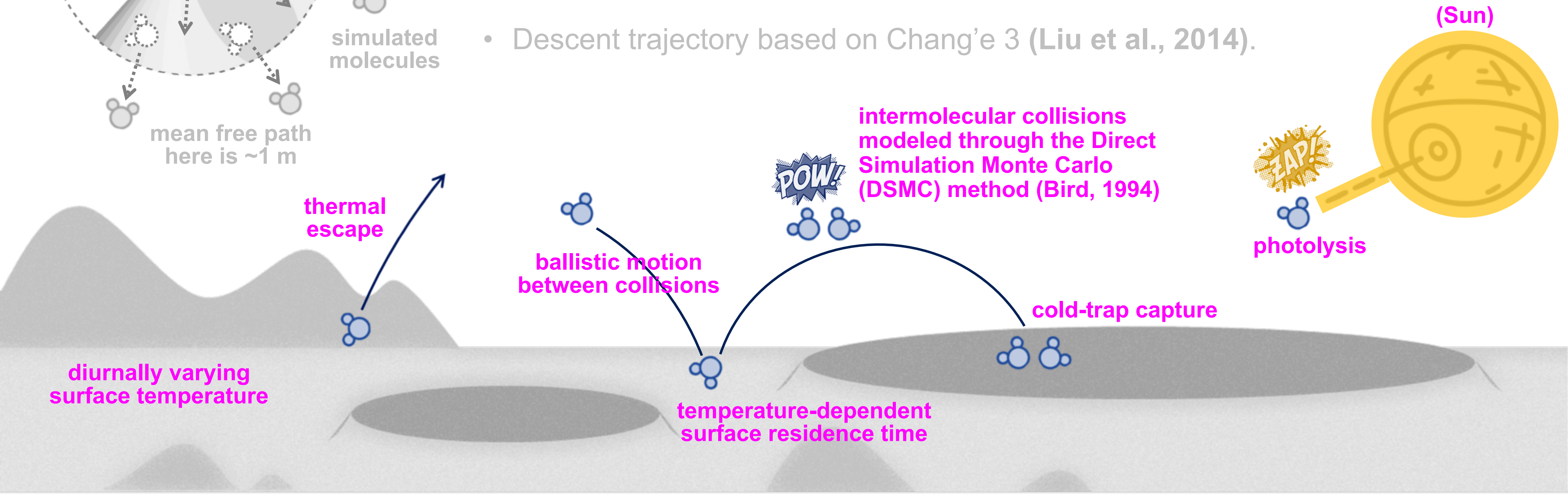


- Specify nozzle exit diameter (0.6 m), thrust (2500 N), combustion chamber conditions **(Lee, 2017)**, exit Mach number (5). H_2O ~33% of exhaust.
- **Simulated molecules** generated within a **virtual source region** using an analytical expression for density **(Roberts, 1966)**; velocity and temperature from isentropic flow relations. **~43 kg H_2O released over 155s**.
- Descent trajectory based on Chang'e 3 **(Liu et al., 2014)**.

To Make An Exosphere From Scratch



- Specify nozzle exit diameter (0.6 m), thrust (2500 N), combustion chamber conditions **(Lee, 2017)**, exit Mach number (5). H_2O ~33% of exhaust.
- **Simulated molecules** generated within a **virtual source region** using an analytical expression for density **(Roberts, 1966)**; velocity and temperature from isentropic flow relations. **~43 kg H_2O released over 155s**.
- Descent trajectory based on Chang'e 3 **(Liu et al., 2014)**.



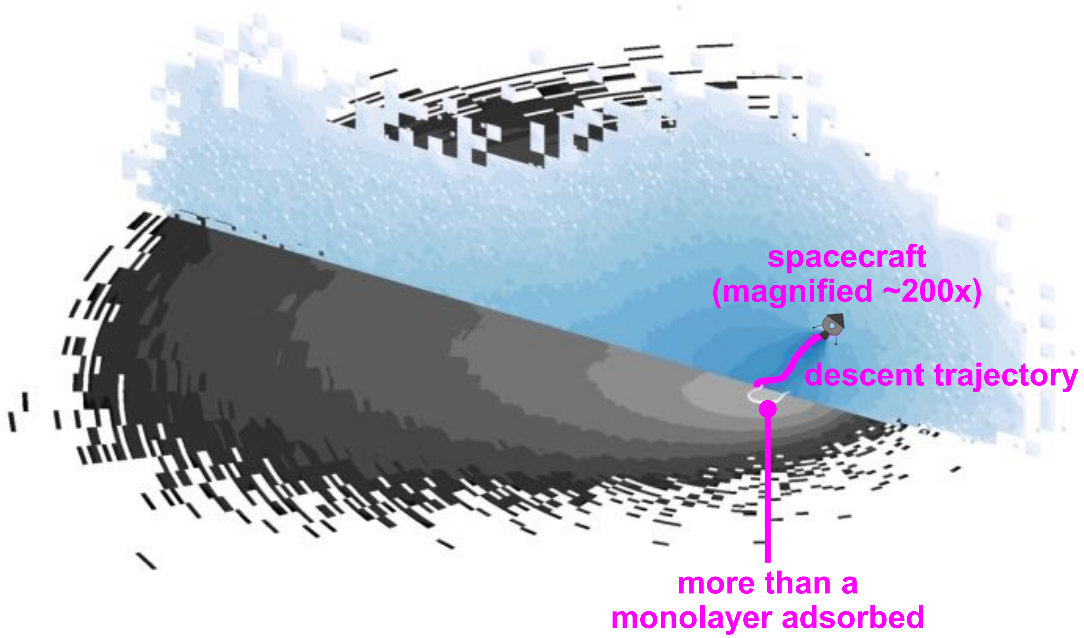
parvathy.prem@jhuapl.edu

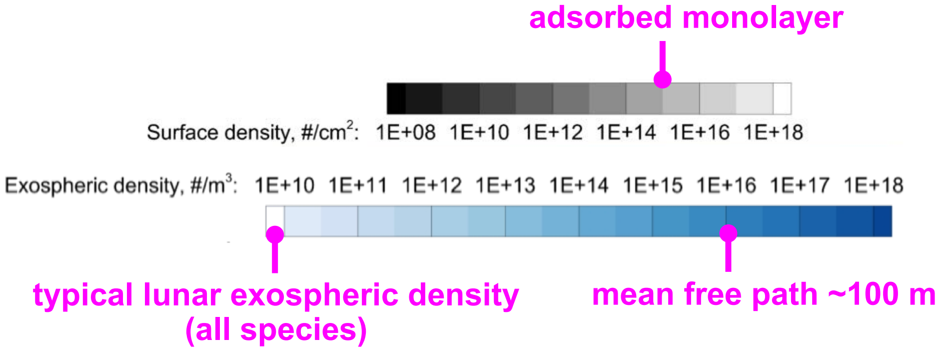
A Nominal Descent

- **70° S, 7 am** lunar local time (T_{surf} ~200 K).
- Surface interaction parameters:
  - Sticking coefficient = 1.0.
  - **Desorption activation energy** = 0.7 eV (≈ 67.5 kJ/mol).
  - 100% thermalization.
- Things to think about:
  - Scale of area affected.
  - Enhancement in exospheric density.
  - Surface adsorption.
  - Mean free path vs. scales of interest.

5 s into powered descent

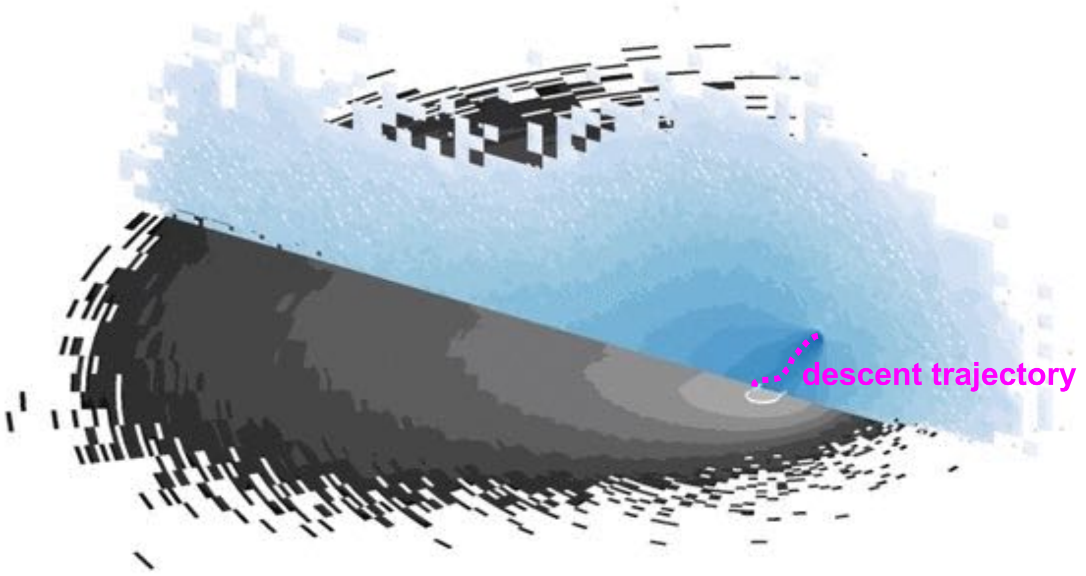
1 km

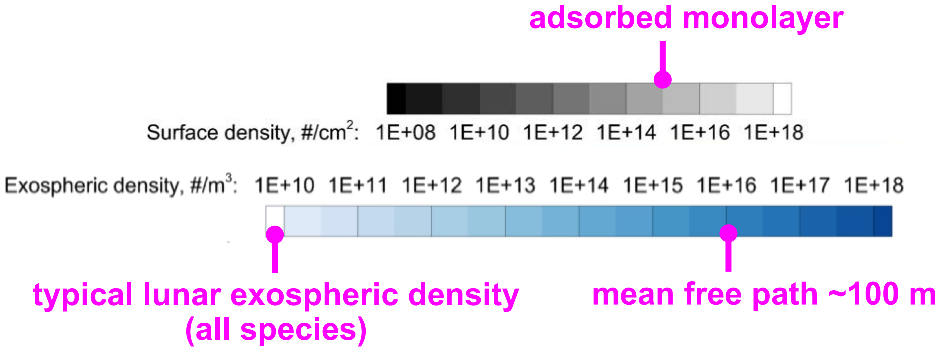




A Nominal Descent

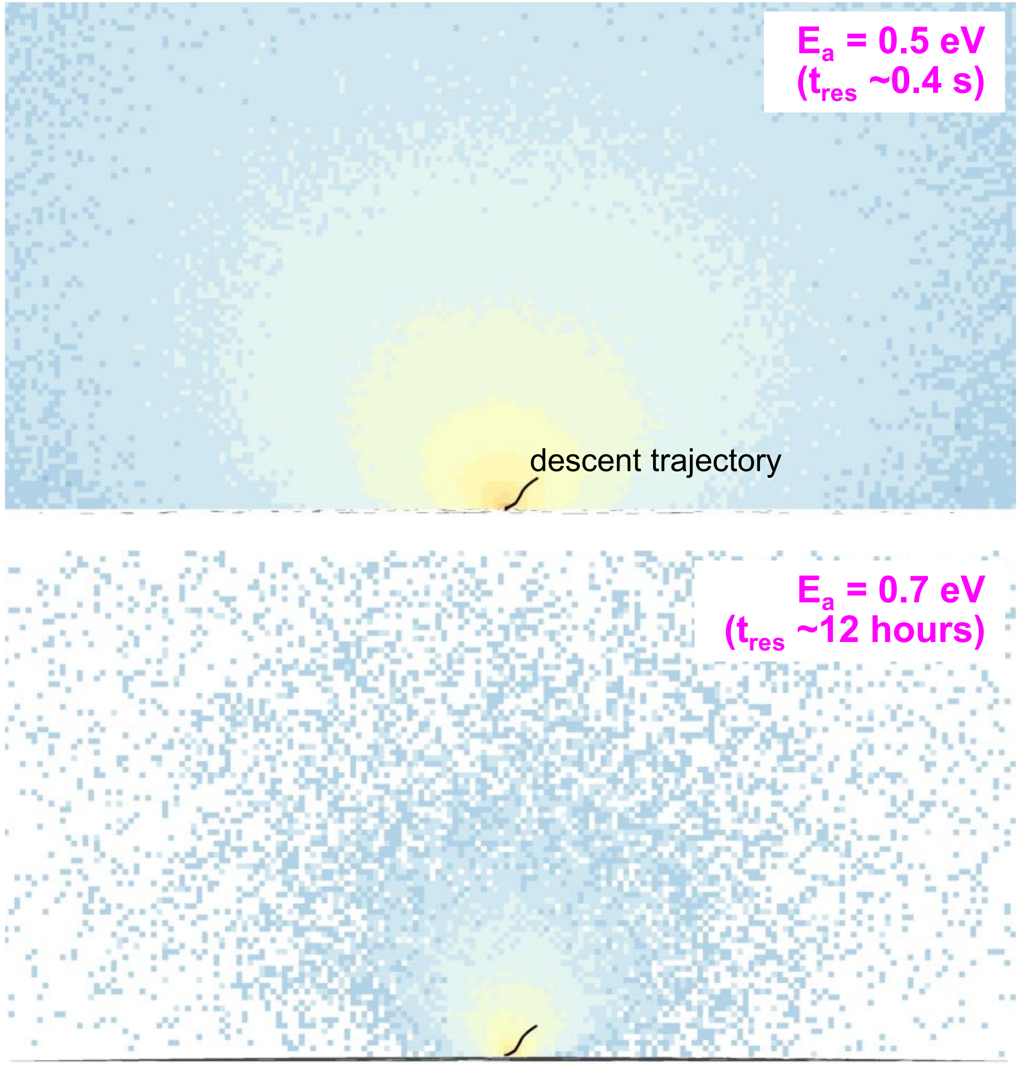
- **70° S, 7 am** lunar local time (T_{surf} ~200 K).
- Surface interaction parameters:
  - Sticking coefficient = 1.0.
  - **Desorption activation energy** = 0.7 eV (≈ 67.5 kJ/mol).
  - 100% thermalization.
- Things to think about:
  - Scale of area affected.
  - Enhancement in exospheric density.
  - Surface adsorption.
  - Mean free path vs. scales of interest.





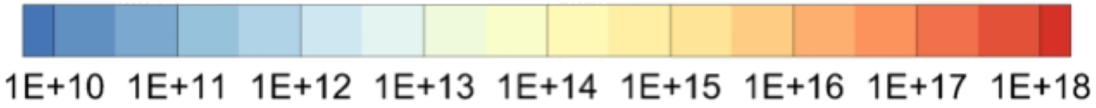
Deducing Surface Interaction Parameters from Observations

- Consider the same landing scenario, varying only **desorption activation energy,** E_a (0.5 eV vs. 0.7 eV); mean **surface residence time, t_{res}** = $(1/\nu)\exp(\mathbf{E_a}/k_B T_{surf})$
- This affects the balance between adsorbed and migrating water vapor.



after 155 s of powered descent
altitude 1.8 km to 50 m | lateral traverse ~1.8 km

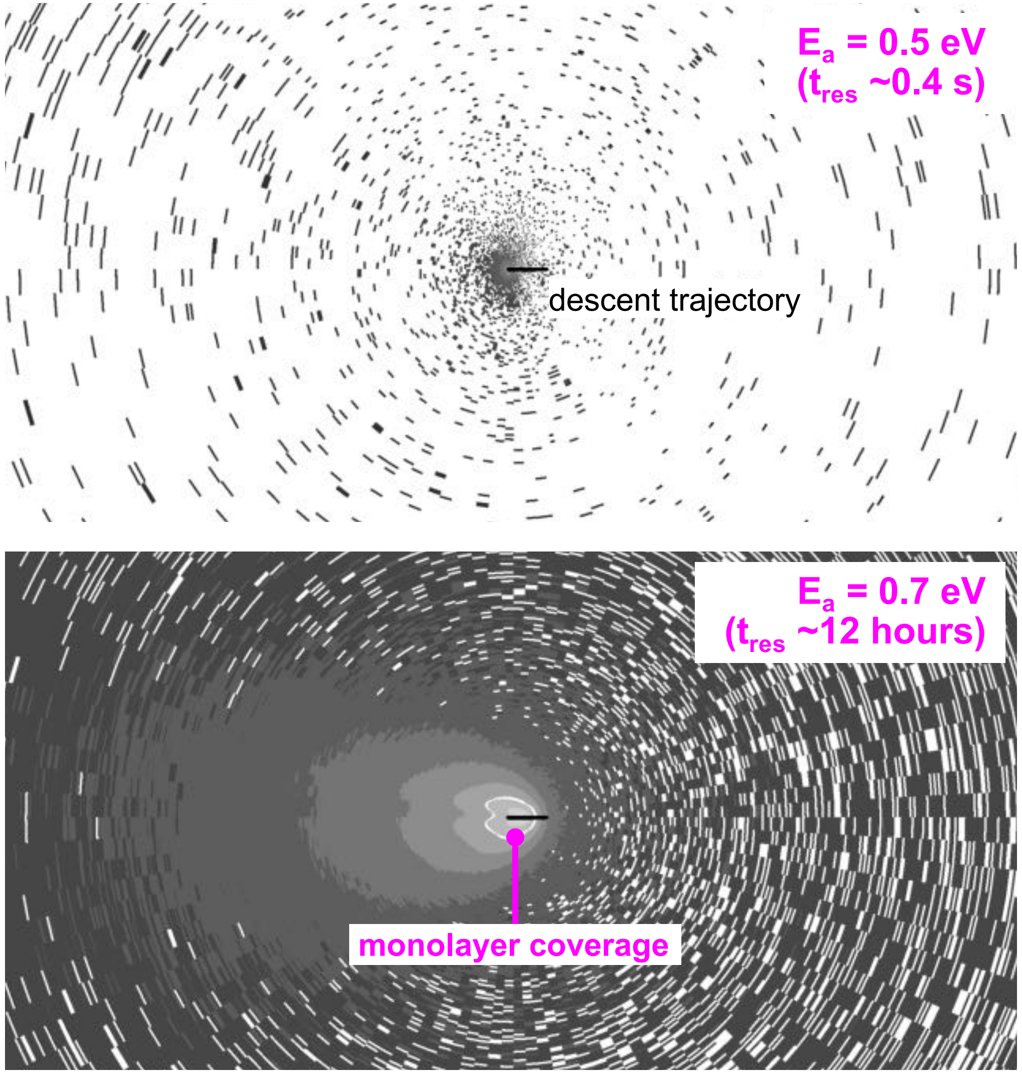
Exospheric density (#/m³) in the descent plane



parvathy.prem@jhuapl.edu

Deducing Surface Interaction Parameters from Observations

- Consider the same landing scenario, varying only **desorption activation energy,** E_a (0.5 eV vs. 0.7 eV); mean **surface residence time, t_{res}** = $(1/\nu)\exp(\mathbf{E_a}/k_B T_{surf})$
- This affects the balance between adsorbed and migrating water vapor.
- For perspective:
  - Recent LAMP observations suggest the presence of migrating H_2O, at <1% monolayer surface coverage **(Hendrix et al., 2019)**.



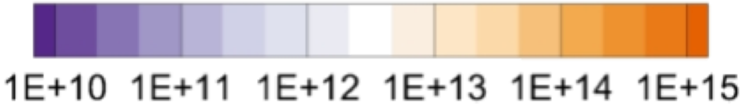
after 155 s of powered descent
altitude 1.8 km to 50 m | lateral traverse ~1.8 km

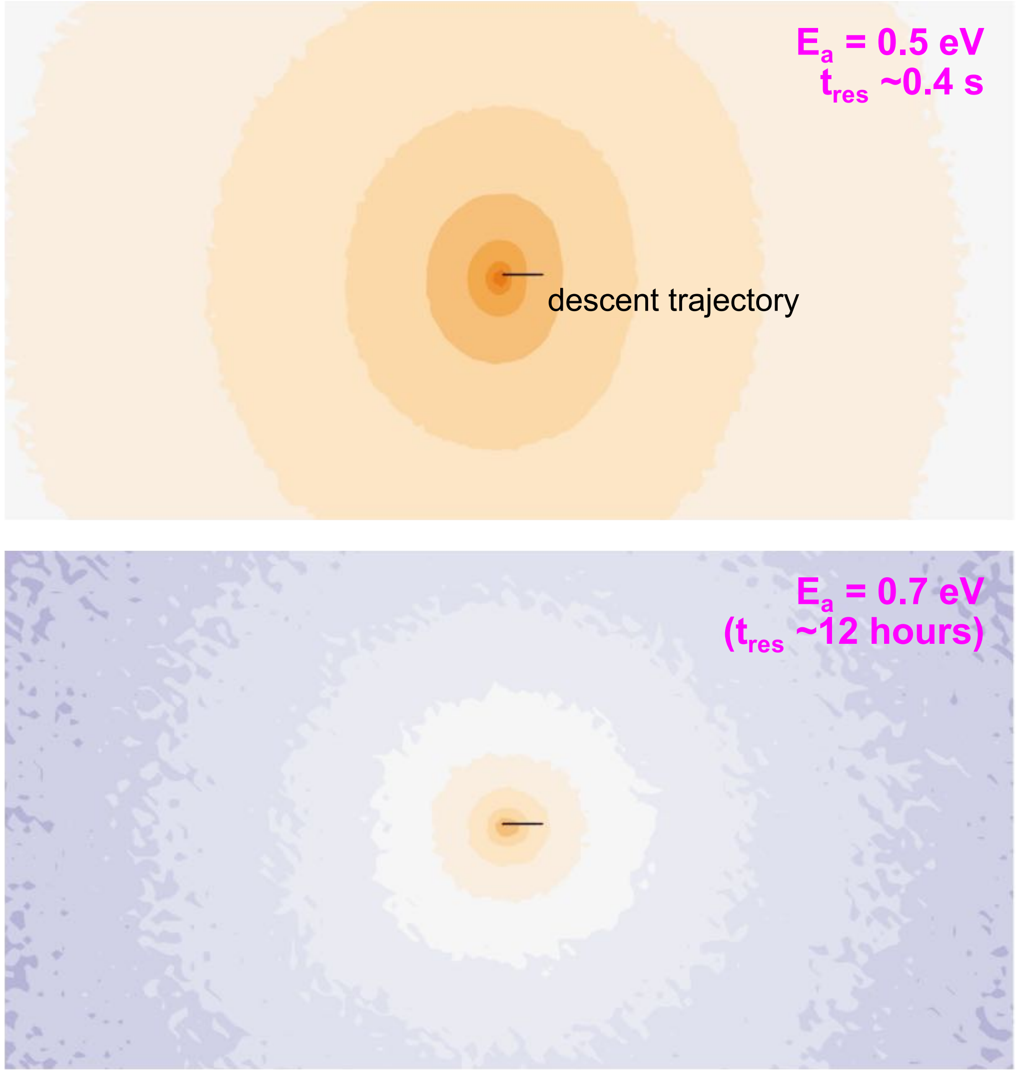
Surface density (#/cm²) of adsorbed molecules

Deducing Surface Interaction Parameters from Observations

- Consider the same landing scenario, varying only **desorption activation energy,** E_a (0.5 eV vs. 0.7 eV); mean **surface residence time,** $\mathbf{t_{res}} = (1/\nu)\exp(\mathbf{E_a}/k_B T_{surf})$
- This affects the balance between adsorbed and migrating water vapor.
- For perspective:
  - Recent LAMP observations suggest the presence of migrating H_2O, at <1% monolayer surface coverage **(Hendrix et al., 2019)**.
  - Elemental column densities detected by LAMP 30 – 60 s after LCROSS ranged from 10^9 to 10^{13} #/cm^2 **(Gladstone et al., 2010)**.

Column density (#/cm²) of exospheric molecules



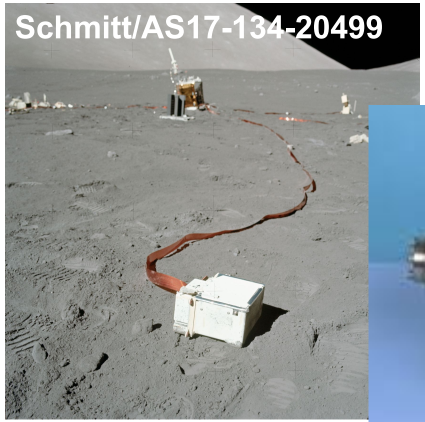


after 155 s of powered descent
altitude 1.8 km to 50 m | lateral traverse ~1.8 km

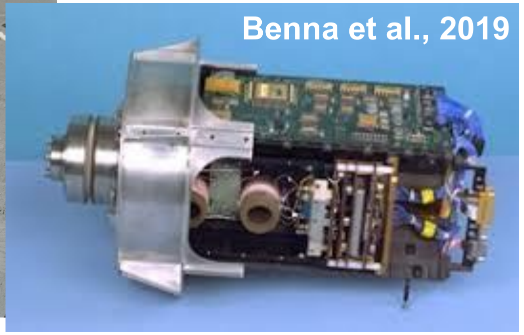
Exospheric Science at Lander Scale

*e.g., Bandfield et al., 2015, Rubanenko & Aharonson, 2017

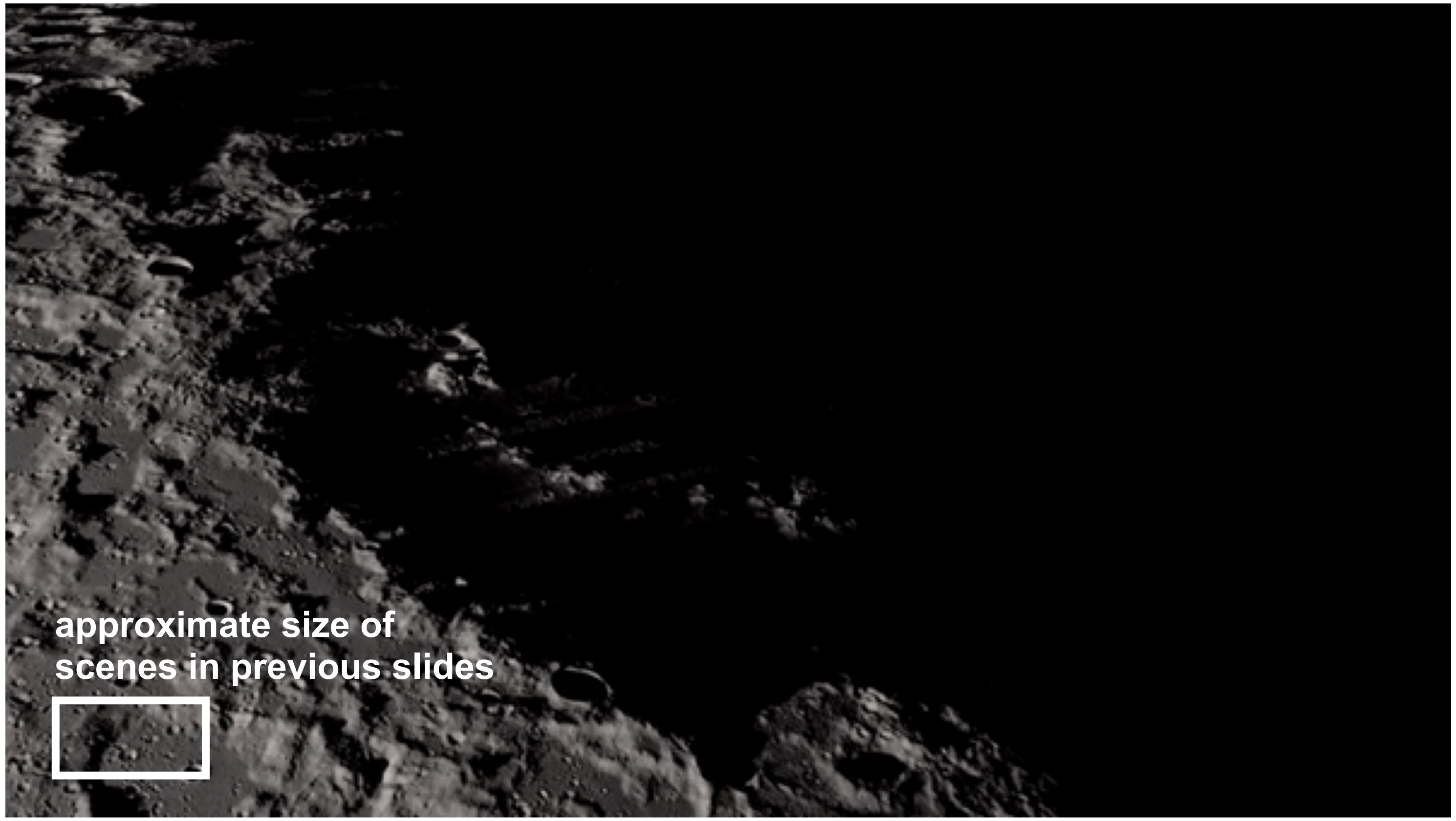
- Lunar surface temperature can vary dramatically over a range of scales* particularly at **high solar incidence** angles (dawn and high latitudes).
- How significant a role does this play in exospheric science at the lander and rover scale?



Lunar Atmospheric Composition Experiment (LACE)



Surface and Exosphere Alterations by Landers (SEAL)



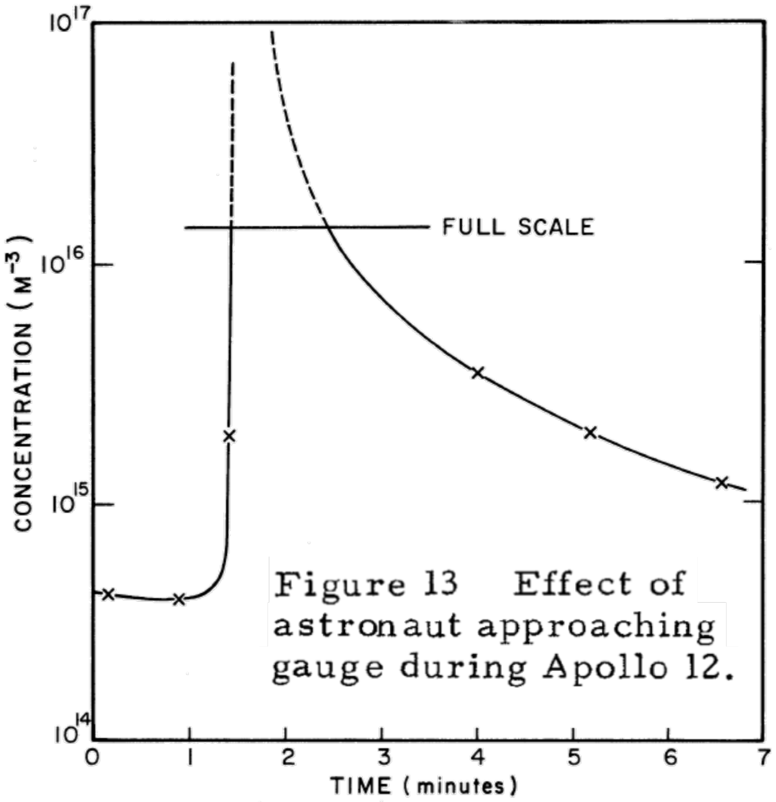
Sunrise over Schrödinger basin, Ernie Wright/NASA's Scientific Visualization Studio

Molecules travel a few hundred km in a few hundred seconds through ballistic hops. (For perspective, Schrödinger basin is ~300 km wide.)

Close Encounters of the Second Kind

(inspired by conversations with
Edward L. Patrick, SwRI)

- Spacecraft exhaust propagation is a case study in how the systems that we build may (typically temporarily) alter their operational environments – with **implications for exploration and science**.

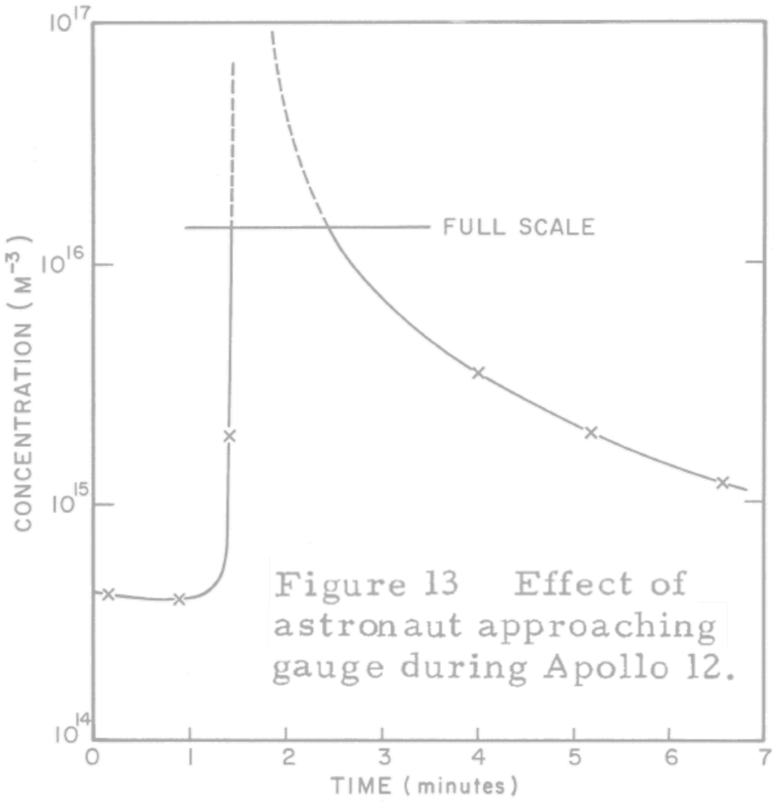


from the Final Report for Cold Cathode
Gauge Experiment (Johnson et al., 1974)

Close Encounters of the Second Kind

(inspired by conversations with
Edward L. Patrick, SwRI)

- Spacecraft exhaust propagation is a case study in how the systems that we build may (typically temporarily) alter their operational environments – with **implications for exploration and science**.

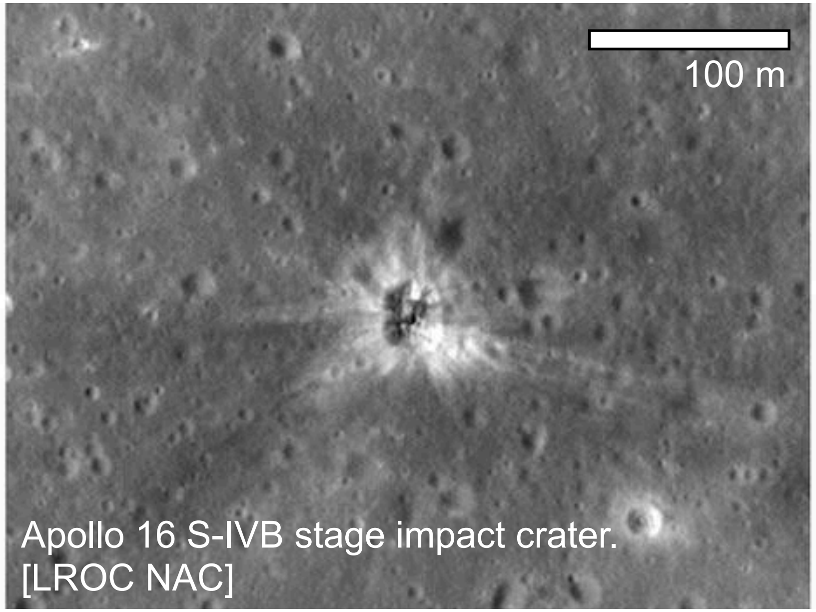


from the Final Report for Cold Cathode Gauge Experiment **(Johnson et al., 1974)**

(Benna et al., 2019)

Lunar soil hydration constrained by exospheric water liberated by meteoroid impacts

M. Benna[1,2]*, D. M. Hurley[3], T. J. Stubbs[1], P. R. Mahaffy[1] and R. C. Elphic[4]



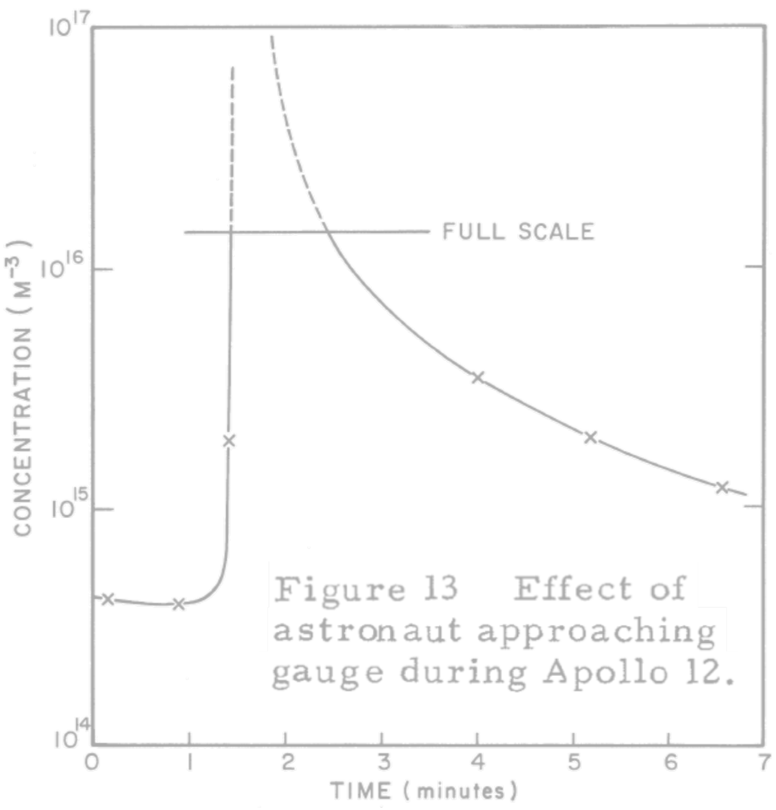
Apollo 16 S-IVB stage impact crater.
[LROC NAC]

another sort of meteoroid?

Close Encounters of the Second Kind

(inspired by conversations with Edward L. Patrick, SwRI)

- Spacecraft exhaust propagation is a case study in how the systems that we build may (typically temporarily) alter their operational environments – with **implications for exploration and science**.

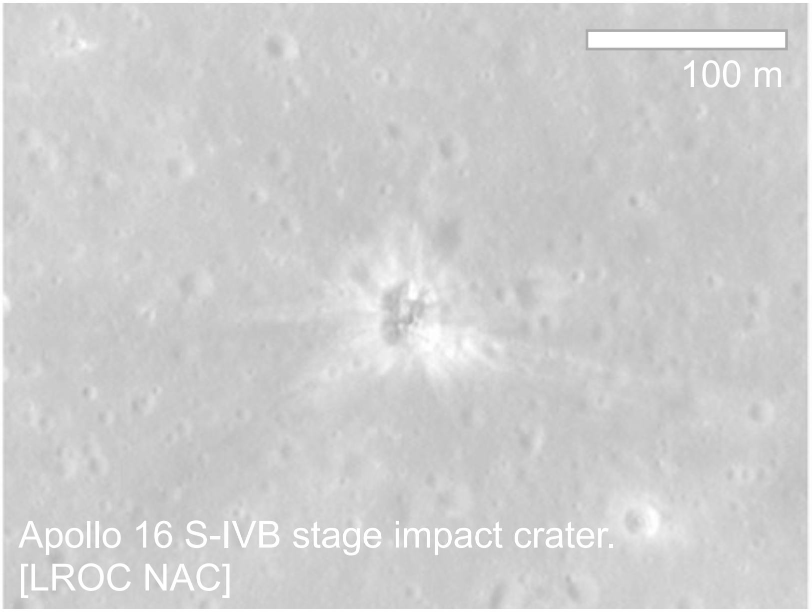


from the Final Report for Cold Cathode Gauge Experiment **(Johnson et al., 1974)**

(Benna et al., 2019)

Lunar soil hydration constrained by exospheric water liberated by meteoroid impacts

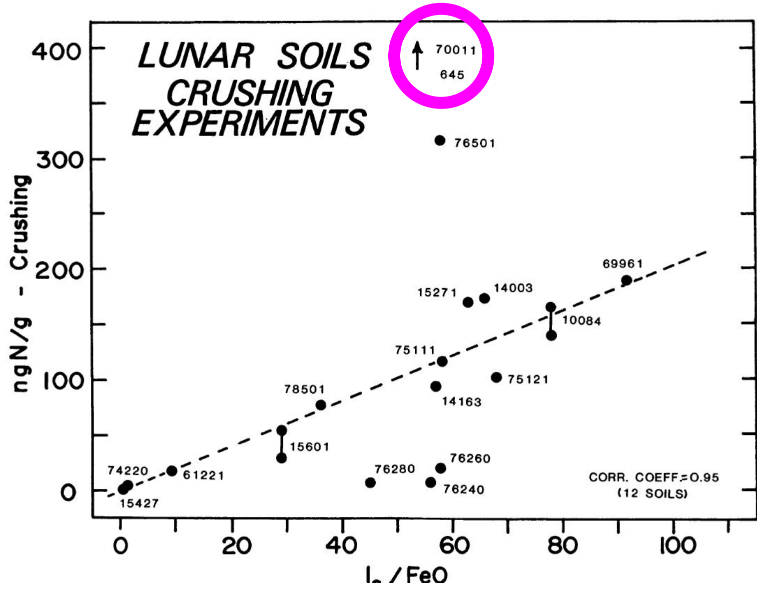
M. Benna[1,2]*, D. M. Hurley[3], T. J. Stubbs[1], P. R. Mahaffy[1] and R. C. Elphic[4]



another sort of meteoroid?

Lunar soils, nitrogen content vs. maturity **(Gibson & Andrawes, 1978)**

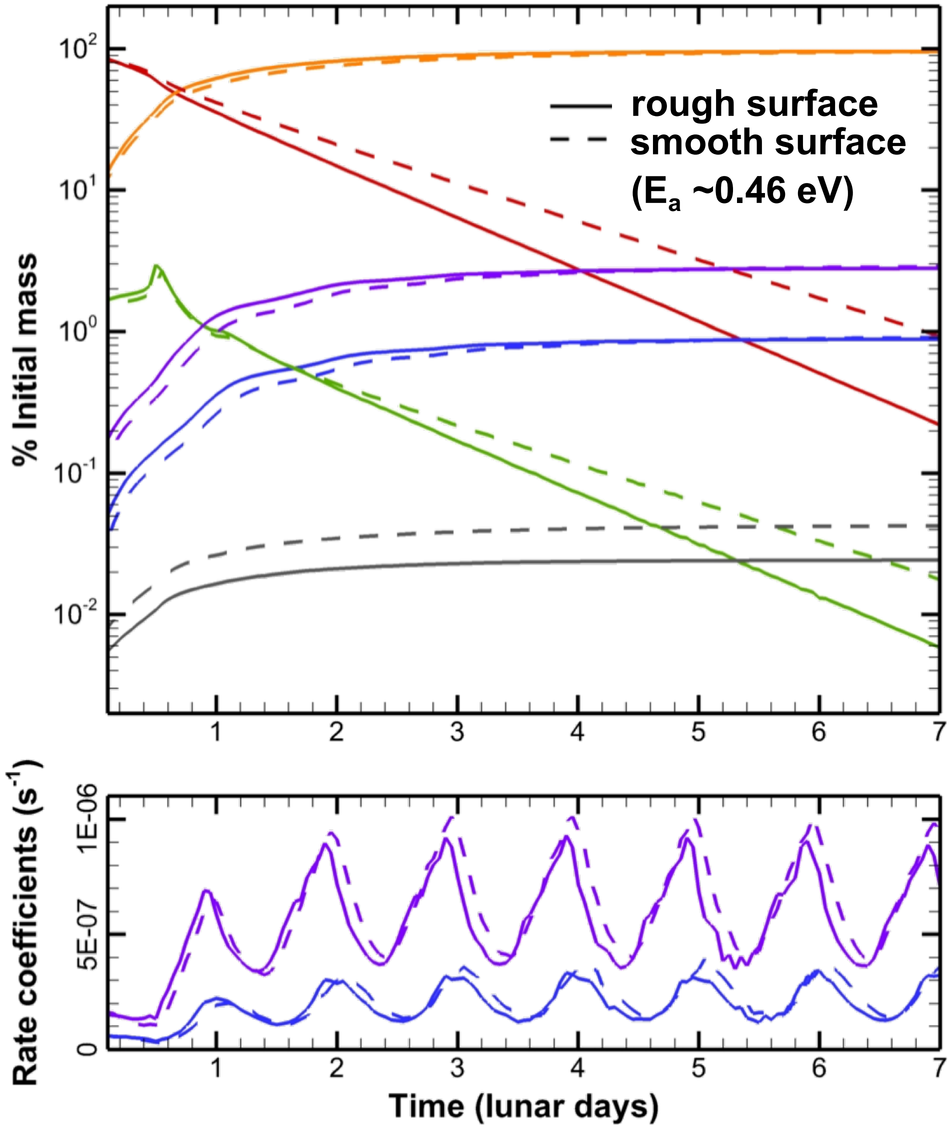
70011 (collected beneath lunar module)



Modeling Long-Term Volatile Transport and Loss

- Previous work (e.g., Prem et al, 2018) indicates that a quasi-steady exosphere should be established within 1-2 lunar days.
- **Rate of exospheric decay** is sensitive to surface interaction parameters (including desorption activation energy).
- **Diurnal variability** in flux to surface.

from Prem et al, 2018



Top: Percentage of initial mass **photodestroyed**, trapped at **south** and **north** polar cold traps, lost to **thermal escape**, **adsorbed** and **aloft** vs. time.

Bottom: **south**/**north** polar cold-trapping rate coefficients (for comparison, **photodestruction** rate coefficient is **~1.2E-05 s^{-1}**).

parvathy.prem@jhuapl.edu

Modeling Long-Term Volatile Transport and Loss

- Previous work **(Prem et al, 2018)** indicates that a quasi-steady exosphere should be established within 1-2 lunar days.
- **Rate of exospheric decay** is sensitive to surface interaction parameters (including desorption activation energy).
- **Diurnal variability** in flux to surface.
- **Work in progress:** modeling the transition to quasi-steady state of a spacecraft-generated exosphere.

from Prem et al, 2018

(https://xkcd-excuse.com/)

Top: Percentage of initial mass **photodestroyed**, trapped at **south** and **north** polar cold traps, lost to **thermal escape**, **adsorbed** and **aloft** vs. time.

Bottom: **south**/**north** polar cold-trapping rate coefficients (for comparison, **photodestruction** rate coefficient is **~1.2E-05 s^{-1}**).

Summary and Conclusions

- Almost any landed lunar mission will be an active volatile release experiment.

- In the immediate aftermath of a nominal descent that releases water vapor as an exhaust gas, the **surficial** and **exospheric** distribution of water is quantifiably sensitive to **gas-surface interaction parameters**.

- During a nominal descent, regions **> 10 km from the landing site** may be exposed to exhaust gases.

- Priorities from a modeling perspective:
  - How long does it take for exhaust gases to be **globally dispersed**?
  - How much water migrates to polar **cold traps**, and how is it **distributed**?
  - How sensitive is the exospheric response to landing **latitude**?

- Understanding **how spacecraft alter the lunar environment**, and **sustained observations** of the lunar exosphere could play key roles in both science and exploration.

parvathy.prem@jhuapp.edu